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Impacts of historic climate variability and land use change on winter wheat climatic productivity in the North China Plain during 1980–2010

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ABSTRACT

As one of the most populous countries, China has policies protecting the amount of land available for crop production, but it does not consider the quality of land. Thus, an important issue is the impact on crop production by land use change under such policies and by notable climate variability during the past decades. Using a productivity attenuation method, we estimated the climatic productivity of winter wheat (WWCP) in the North China Plain, based on land use classification data and daily weather data from 1980 to 2010. Impacts of historic climate variability and land use change on WWCP were quantified. Results indicate: (1) on average, WWCP for newly-increased dry land was lower than that for the lost land, which may result in reduced land quality associated with conversion. (2) In recent years, the increasing area of dry land provided sufficient wheat yield to compensate for the loss resulted from reduction of WWCP. (3) Both historic climate variability and land use change decreased WWCP, but the effects of the latter (within −1%) were less than those of the former (about −3%). Given the scarce land resource and rapidly growing food demand, the approach through expanding the area of cultivated land to maintain grain yield is not a long-term guarantee of food security. Thus, cultivated land conservation policy should shift from protecting land quantity into preserving land productivity. In addition, agriculture policies should further emphasize the critical role of adaptation strategies in coping with climate change. Obtaining higher yield production will depend upon adopting adaptation measures which could effectively mitigate effects of dramatic climate change or even take advantage of possible climate conditions.

1. Introduction

The global demand for grain has rapidly increased along with an ever-increasing human population and improvements in lifestyle. Based on current trends, at least a 100% increase in agricultural production from 2005 to 2050 could satisfy global grain demands at current living standards; however, if lifestyles of all nations were to reach those of developed countries, this demand would be much higher (Tilman et al., 2011). Unprecedented climate change continues to influence agriculture and crop production, making it increasingly challenging to feed this rapidly growing population without harming the environment (Lal, 2016). China has successfully fed its resident 22% of the world's population by relying on only 7% of its cultivated land. However, environmental stress has increased as the center of grain production has shifted north. It is currently unknown whether China has the resources to remain self-sufficient in food into the future (You et al., 2011). The impact of change in climate and land use on crop production needs more research in order to better understand future challenges regarding food self-sufficiency. These results could provide a valuable reference for stakeholders as well as policymakers to make better solutions for addressing issues related to food security and climate change.

Since the occurrence of a change in climate is unequivocal (IPCC, 2013), many researchers have studied temporal–spatial changes in grain productivity under changing climatic conditions, especially under increasing temperatures (Wu et al., 2006; Lv et al., 2013). Many studies indicate that global warming is harmful to crop production, declaring that an increase in temperature during the growing season results in heat stress and shortens the length of the growing season, with a consequent reduction in crop yield (You et al., 2009; Tack et al., 2015). A contra-argument from some researchers states that increased temperature enables crops to grow in those regions that were previously considered too cold, which has resulted in a northward shift of cropping areas into newly expanded arable regions, and has thus improved potential crop yield (Xia et al., 2014; Yang et al., 2015). Furthermore, increasing temperatures could accelerate crop growth and development and lead to a higher cumulative biomass and yield (Sommer et al.,

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2013). Regardless of changes in crop yield, it seems to be widely accepted that climate warming is the most important environmental factor to affect crop productivity or yield potential. Despite the latter consensus, several recent studies suggest that solar radiation contributes more to the reduction of crop yield potential than temperature (Chen et al., 2013; Yang et al., 2014). These studies indicate that the decrease in solar radiation during the growing season is more pronounced than the increase in temperature in these areas. According to Lobell et al. (2009), yield potential, for any given site and growth season, is influenced by solar radiation, temperature, and water supply. Thus, considering all three climatic factors (radiation, temperature, precipitation) at the same time could better estimate the impact of climate change on crop yield potential. Relative research results could support implementation of region-specific adaptation strategies, which is critical for coping with climate change and further maintaining and improving food production (IPCC, 2014).

Land is another key environmental factor for crop development and production, as it provides the habitat for crops to grow. Crop yield potential is influenced by land use change because the reclamation and abandonment of cultivated land alters the quality of the total land area for crop production. The conversion of agricultural land to industry, infrastructure, and residential uses continues to take place worldwide due to economic development. Countries in Europe, North America, and East Asia have consequently lost good arable land during periods of economic development (Seto et al., 2000; Ramankutty et al., 2002). Since the implementation of the reform and openness policies in 1978 in China, the effects of urbanization and industrialization on land use, driven by economic growth, have become apparent and cultivated land has been converted to nonagricultural uses, such as urban housing and industry (Yang and Li, 2000; Shi et al., 2014; Liu et al., 2015). As the center of grain production has shifted northwards, water shortage has further restricted the sustainable development of cultivated land, causing a decrease in quality and potential land productivity from the newly-increased land (You et al., 2011; Qin et al., 2013). The lost cultivated land is generally superior to the newly-increased cultivated land with regard to both natural conditions and farming suitability; therefore, the conversion of different land use types irreversibly damages the quality of cultivated land as a whole and thereby reduces grain productivity (Deng et al., 2006; Liu et al., 2015). Although China has always emphasized the need to retain at least 1.8 billion mu (15 mu is equal to 1 ha) of cultivated land, a clear statement on maintaining land quality has never been enacted (Ministry of Land and Resources, 2008, 2016). These points lead to the following question: Have the land use changes in China since 1980 harmed the nation's ability to guarantee grain demand for the future? To answer this question, it is necessary to quantify the effects of land use change on grain productivity. The latter is an essential scientific issue, requiring a precise estimate of the cultivated area and grain productivity needed to satisfy grain demand; this in turn will provide a reference for adjusting land policies and guaranteeing food security (Tao et al., 2009; Tilman et al., 2011).

The North China Plain (NCP) is nationally one of the most important areas of agricultural production; it grows 71% of China's wheat grain (National Bureau of Statistics of China, 2015), a level of output that is critical for the country (Xiao and Tao, 2014). However, wheat production in the NCP currently faces multiple pressures, including water scarcity (Luo et al., 2018), removal of cultivated land for other purposes, and climate change (Chen et al., 2013). To ensure Chinese food security, wheat production in the NCP deserves more attention from researchers and policymakers. Therefore, in this study, we investigated impacts of changes in climate and land use on wheat production in the NCP under the background of current cultivated land conservation policy and ongoing climate change. Based on our results, we further generated policy implications for China's food security, sustainable agriculture development, and adaptations for climate change.

2. Data and methods

2.1. Study area and data

The NCP, one of the most important areas of agricultural production in China, was selected as the study region. This area, also known as the Huang-huai-hai Plain, is the second largest plain in China and is located between 31.28° and 41.06°N and 111.87° and 120.91°E. It includes the cities of Beijing and Tianjin, the south of Hebei Province, the west of Shandong Province, the east of Henan Province, and the northern parts of Jiangsu and Anhui Provinces. The NCP has a double cropping system of winter wheat–summer maize that contributes 71% of the national wheat and 33% of the national maize production, but only covers approximately 25% of the total arable land and less than 7% of the total water resources of China (National Bureau of Statistics of China, 2015).

The fundamental data used in the current study included the raster data of land use classification in years of 1990, 2000, and 2010, available from the Data Center of Resources and Environmental Sciences of Chinese Academy of Sciences at http://www.resdc.cn/Default.aspx, and daily weather data at meteorological stations, available from the China Meteorological Data Website at http://data.cma.cn/site/index.html. Land use classification data was formatted as a grid with a resolution of 1 km. The land use classification data contained six land use types in level 1, including cultivated land, woodland, grassland, water body, built-up area and unused land, and 25 land use types in level 2. Cultivated land was classified into dry land and paddy field in level 2. The daily weather data covered a period from 1 January 1980 to 31 December 2010 at 45 weather stations in the NCP (Fig. 1), including nine metrics of seven climatic factors (average air pressure, average wind speed, average vapor pressure, average relative humility, sunshine duration, precipitation, average, minimum and maximum temperatures).

The NCP covers a total area of 468,300 km^2 and the majority of land is under cultivation, which occupies over 75% of the total area, with the majority of this being dry land. The percentage of each land use type present in the NCP in 1990, 2000, and 2010, as well as the dry land conversion during the period of 1990–2000 and 2000–2010, are presented in Table 1. From 1990 to 2000, the newly-increased dry land (the land being converted to dry land from other land use types) was less than the lost dry land (the land being converted to other land use types from dry land), which caused a net reduction in total dry land. In contrast, the area of dry land showed a net increase from 2000 to 2010. During these two periods, the major contributor to newly-increased dry land were different: Between 1990 and 2000, it was mainly converted from paddy fields, accounting for over 25% of the total area of newly-increased dry land. From 2000 to 2010, built-up area became the major contributor, superseding both woodland and paddy fields. However, the conversion pattern of lost dry land was similar. Most of the lost dry land was converted into built-up area during both periods; nevertheless, the conversion rate from 1990 to 2000 was lower than that between 2000 and 2010.

2.2. Climatic productivity simulation method

Climatic productivity is defined as the maximum possible yield (yield potential) that an adapted crop may be expected to produce under a given climate and water supply, and for which nutrients, pests, disease, and weeds are optimally managed (Horie, 1987). Under irrigation conditions, the water requirement is met, meaning there is no water stress; while under rain-fed conditions, water is limited and precipitation should be considered. Climatic productivity in a given environment can be estimated using crop models. "Productivity attenuation method" is a step-by-step method that revises photosynthetic productivity, photosynthetic thermal productivity, climatic productivity, and farmland productivity using environment factors to estimate the productivity (Liu et al., 2005). This method originates from

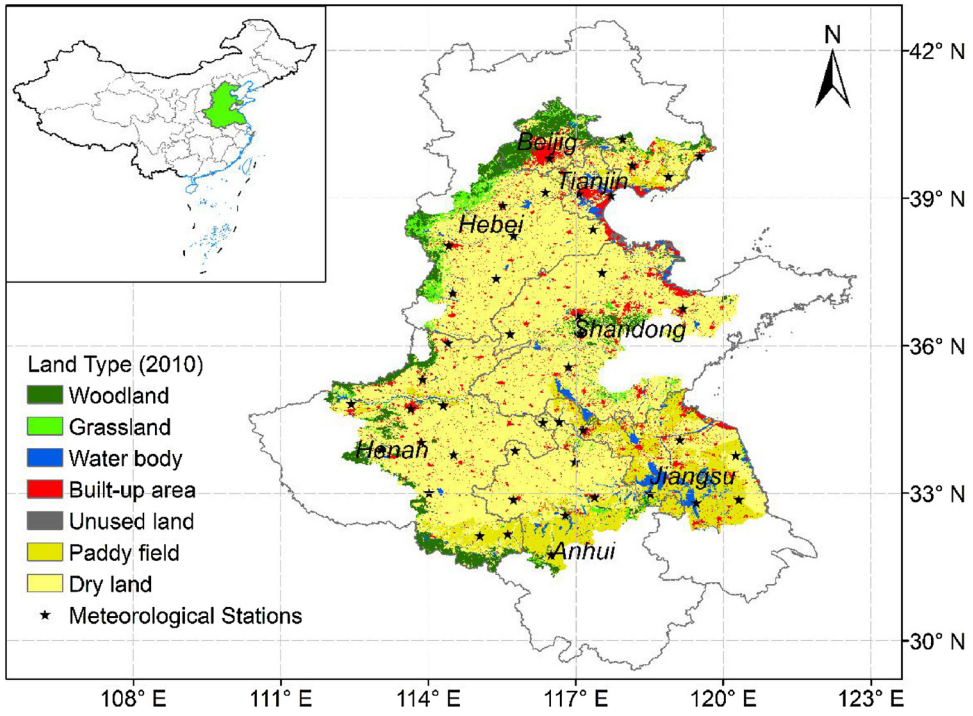

Fig. 1. The location of the NCP and its land use classification in 2010.

an estimation of maximum crop productivity proposed by Loomis and Williams (1963); it has developed into its current form after a series of amendments in China (Liu et al., 2005). Compared with crop growth models based on the dynamic growth process (Lobell and Asseng, 2017), this method does not require many input data for calibration and validation and is better suited for large-scale estimation of crop yield (Liu et al., 2005).

Here, we used the productivity attenuation method to estimate climatic productivity and the equation is as follows:

$$Y = (\Sigma Q_i) \times f(Q) \times f(T) \times f(R) \quad (1)$$

where Y (kg ha^{-1}) is the climatic productivity per unit area. ΣQ_i (MJ m^{-2}) is the total solar radiation during the crop growing season and Q_i is the monthly solar radiation during the growing season, accumulated from daily solar radiation. Daily solar radiation is calculated based on daily sunshine duration, using the recommended method in the FAO-56 model. The $f(Q)$, $f(T)$, and $f(R)$ are the light-effective, temperature-effective, and water-effective coefficients of crop growth and production formation, respectively. More details about these calculations are presented in the supplementary materials (Text S1).

Winter wheat grown in the NCP is irrigated, but the NCP has been suffering serious water issues such as groundwater overexploitation, decline, and overdrafts (Luo et al., 2018). Stopping irrigation might be a possible management option to address these problems (van Oort et al., 2016). Thus, here we focused on winter wheat climatic productivity under rain-fed conditions (no irrigation). Winter wheat planted in the NCP was sown in October and harvested in June of the next year (Sun et al., 2011; Lu and Fan, 2013); thus, the growing season for winter wheat in the study region included the period from 1 October to 30 June of the following year. In order to estimate the climatic productivity of winter wheat (WWCP), daily weather data were added up each month and then were input to calculate the light-effective, temperature-effective, and water-effective coefficients.

2.3. Analysis of climate change and land use change on climatic productivity

The study period (1980–2010) was divided into three sectors: from 1980 to 1990 (1980s), from 1990 to 2000 (1990s), and from 2000 to 2010 (2000s). The mean values for different climatic factors (average temperature, precipitation, and solar radiation) and the WWCP for each station were calculated on a decade scale. Pearson's correlation

Table 1
Land use status and dry land conversion in the North China Plain.

Period	Land conditions	Cultivated land (%)		Woodland (%)	Grassland (%)	Water body (%)	Built-up area (%)	Unused land (%)
		Dry land	Paddy field					
1990	Land use status	67.62[a]	12.22[a]	6.57[a]	5.00[a]	2.42[a]	4.86[a]	1.31[a]
From 1990 to 2000	Newly-increased dry land	/	29.88[b]	13.53[b]	24.36[b]	10.04[b]	19.89[b]	2.30[b]
	Lost dry land	/	19.95[c]	18.76[c]	9.52[c]	9.76[c]	38.83[c]	3.18[c]
2000	Land use status	65.07[a]	12.44[a]	7.70[a]	4.28[a]	3.42[a]	6.47[a]	0.61[a]
From 2000 to 2010	Newly-increased dry land	/	20.69[b]	17.72[b]	21.42[b]	7.01[b]	28.07[b]	5.10[b]
	Lost dry land	/	23.12[c]	19.21[c]	3.35[c]	6.35[c]	47.21[c]	0.76[c]
2010	Land use status	66.79[a]	12.00[a]	7.64[a]	2.53[a]	3.37[a]	7.35[a]	0.32[a]

Notes: [a]Percentage of area of each land use type that occupied the total area of the NCP. [b]Percentage of decreasing area of each land use type that occupied the total area of newly-increased dry land. [c]Percentage of increasing area of each land use type that occupied the total area of lost dry land. "Newly-increased dry land" denotes the land being converted to dry land from other land use types. "Lost dry land" denotes the land being converted to other land use types from dry land. The sum of the percentages in any row may not equal 100 because values have been rounded to two decimal places.

Table 2
Modeling conditions of WWCP in the NCP.

Influence factor	Period	Observed climate data	Land use classification data	Calculated Value
/	Reference period (1980s)	1980–1990	1990	Y_{ref}
Climate + Land use	1990s 2000s	1990–2000 2000–2010	2000 2010	Y_{CL}
Climate	1990s 2000s	1990–2000 2000–2010	Same with reference period	Y_C
Land use	1990s 2000s	Same with reference period	2000 2010	Y_L

coefficient was then used to analyze the correlation between each climatic factor and WWCP. A multiple linear regression model was used to describe the relationship between average temperature, precipitation, solar radiation, and WWCP. Initially all station data were divided into the three above-mentioned sectors, with each sample containing 45 data sets; secondly, the data from the 1980s and 1990s were used to establish the regression model. Finally, the data from the 2000s were used to assess the prediction performance of the previously established regression model.

Based on ArcGIS software, WWCP calculated for each station using productivity attenuation method was firstly interpolated and then extracted with the dry land data as the mask to generate a map of WWCP in the NCP, setting the resolution of 1 km. Through overlapping maps of WWCP in various years, the change in WWCP of each grid was obtained. Subsequently, these changes were summed up into 12 different conversion types, indicating changes in WWCP caused by land use change.

In order to isolate impacts of historic climate variability or land use change on WWCP, different climate and land use conditions were addressed to estimate WWCP in the NCP (Table 2). Y_{ref} is used as the reference value of WWCP, which is estimated using climate and land use data in the reference period (1980s). Y_{CL} is the WWCP estimated under the combined effects of changes in climate and land use. By holding land use consistent with the reference period, Y_C is the WWCP that will only change with climate. In contrast, by holding climate consistent with the reference period, Y_L is the WWCP that will only change with land use. Impacts on WWCP caused by historic climate variability or land use change could be estimated by relative changes in average WWCP in a certain period. For example, impacts on climatic productivity caused by combined effects of changes in climate and land use was calculated as Eq. (2):

$$I_{CL} = (Y_{CL} - Y_{ref}) / Y_{ref} \times 100\% \quad (2)$$

where I_{CL} represents impacts on WWCP caused by combined effects of historic climate variability and land use change.

Likewise, impacts on climatic productivity caused by isolated effects of historic climate variability or land use change were calculated as Eqs. (3) and (4), respectively.

$$I_C = (Y_C - Y_{ref}) / Y_{ref} \times 100\% \quad (3)$$

$$I_L = (Y_L - Y_{ref}) / Y_{ref} \times 100\% \quad (4)$$

where I_C represents impacts on WWCP caused by isolated effects of historic climate variability, and I_L represents impacts on WWCP caused by isolated effects of land use change.

Based on Eqs. (2)–(4), impacts on climatic productivity caused by interactive effects of changes in climate and land use could be calculated as Eq. (5):

$$I_C x_L = I_{CL} - (I_C + I_L) \quad (5)$$

where $I_C x_L$ represents impacts on WWCP caused by interactive effects of historic climate variability and land use change.

3. Results

3.1. Spatio-temporal changes of climatic productivity for winter wheat

3.1.1. Trends over time

Over the past 30 years, the average WWCP in the NCP has ranged from 6000 to 12,000 kg ha^{-1}. The mean WWCP has been 9405.14 kg ha^{-1}, which is higher than the modeled yield potential under rain-fed conditions (7300 kg ha^{-1}), also of winter wheat in the NCP, based on the EPIC model (Environment Policy Integrated Climate) in the study of Lu and Fan (2013). This result is likely due to the optimal conditions used in EPIC to estimate yield potential at 43 representative meteorological stations. In their study (Lu and Fan, 2013), conditions were set based on the optimal managements at two agro-meteorological experimental stations, implying that nutrients, pests, disease, and weeds might not be optimally managed at these meteorological stations. Considering yield potential calculated from different models might be difficult to be compared with each other, we further compared our simulated results with those simulated by the same method used here. Results show that our estimation of the mean WWCP at stations belonging to Shandong Province from 1981 to 2010 is 7127 kg ha^{-1}. This figure is quite closed to 7413 kg ha^{-1}, the mean climatic productivity of winter wheat in Shandong Province during the period of 1961–2008, which is also estimated based on the productivity attenuation method (Lian et al., 2012). The coefficient of variation in WWCP during study peirod reached 12.40%, indicating a noticeable inter-annual fluctuation. In particular, peak WWCP occurred in the years 1985, 1990, 1998, and 2004, when it exceeded 11,000 kg ha^{-1} (Fig. 2). Based on a mean value of 30 years, the cumulative anomaly curve indicated that WWCP trends could be divided into three periods: WWCP increased in the 1980s, showed an obvious fluctuation between 1991 and 2004, and then decreased from 2005. However, nonparametric tests suggested that these trends were not significant ($p > 0.05$).

3.1.2. Changes of spatial pattern

Changes of spatial–temporal distribution and spatial patterns of WWCP in the NCP in the years 1990, 2000, and 2010 are presented in Fig. 3. In 1990 (Fig. 3a), WWCP in the NCP exhibited a decreasing spatial pattern from south to north; in particular, WWCP within Jiangsu, Anhui, and Henan (10,000–20,000 kg ha^{-1}) was obviously higher than that within Shandong, Hebei, Beijing, and Tianjin (4000–10,000 kg ha^{-1}). WWCP in the NCP in 2000 (Fig. 3b) and 2010 (Fig. 3c) changed to varying degrees when compared to that in 1990, yet a similar spatial pattern involving a reduction from south to north was found in both years. A similar spatial pattern of yield potential distribution of winter wheat in the NCP has been reported in earlier studies (Wu et al., 2006; Lu and Fan, 2013). From 1990 to 2000 (Fig. 3d), a decreasing trend of WWCP nearly occurred in the entire NCP and its magnitude showed a decrease from west to east. The decrease in magnitude was predominantly within 3000 kg ha^{-1} and that in the east was much larger, at over 3000 kg ha^{-1}, while a tiny area inside Shandong showed a slight increasing trend. The change of spatial pattern for the period of 2000–2010 differed from that of 1990–2000 (Fig. 3e). From 2000 to 2010, areas in which WWCP increased or decreased showed only small differences, within 3000 kg ha^{-1}.

3.2. Impact of historic climate variability on climatic productivity

The effects of historic climate variability on WWCP were analyzed from three aspects: average temperature, precipitation, and solar radiation during the growing season. Fig. 4 suggests that the data points determined from predicted WWCP and the original WWCP were close to the 1:1 line and their Pearson's correlation coefficient reached 0.96

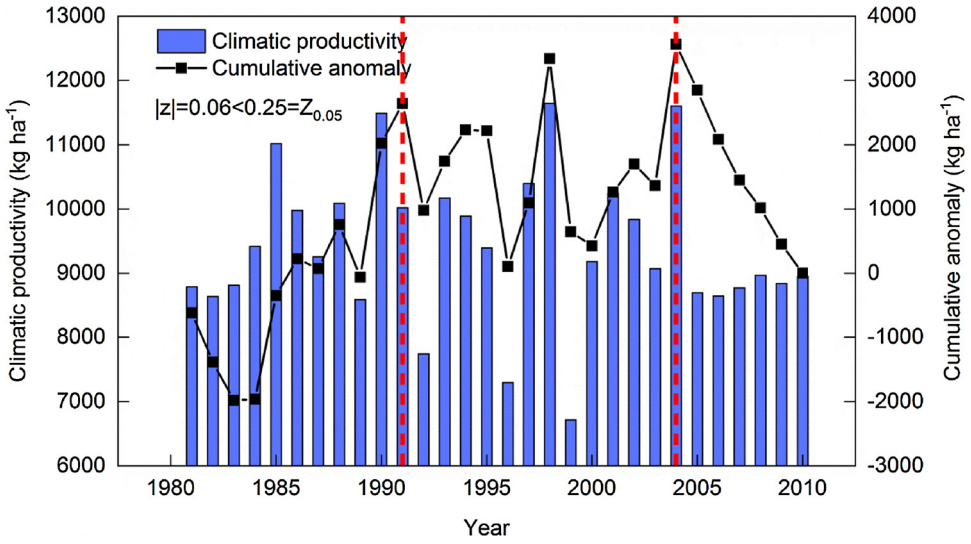

Fig. 2. Time-series plot of WWCP in the NCP, and its cumulative anomaly curve.

($p < 0.01$), which indicates a reasonably good fit and prediction accuracy for the regression model. This shows that this regression model is capable of predicting WWCP based on the average temperature, precipitation, and solar radiation for the growing season. Based on the regression model, results suggest that the WWCP increased 548, 1893, and 2220 kg ha^{-1} respectively, as the average temperature, precipitation, and solar radiation for the growing season increased 1 °C, 100 mm, and 1000 MJ m^{-2}, respectively. Moreover, results also show that precipitation had a much larger influence on WWCP than average temperature or solar radiation during the winter wheat growing season.

3.3. Impact of land use change on climatic productivity

Percentage of area, percentage of total WWCP, and average WWCP of each conversion type for the two periods are presented in Fig. 5. The current study results show that during the period of 1990–2000, although woodland (with a high WWCP of 12,870.89 kg ha^{-1}) converted into dry land accounted for 4.82% of total area change, much more dry

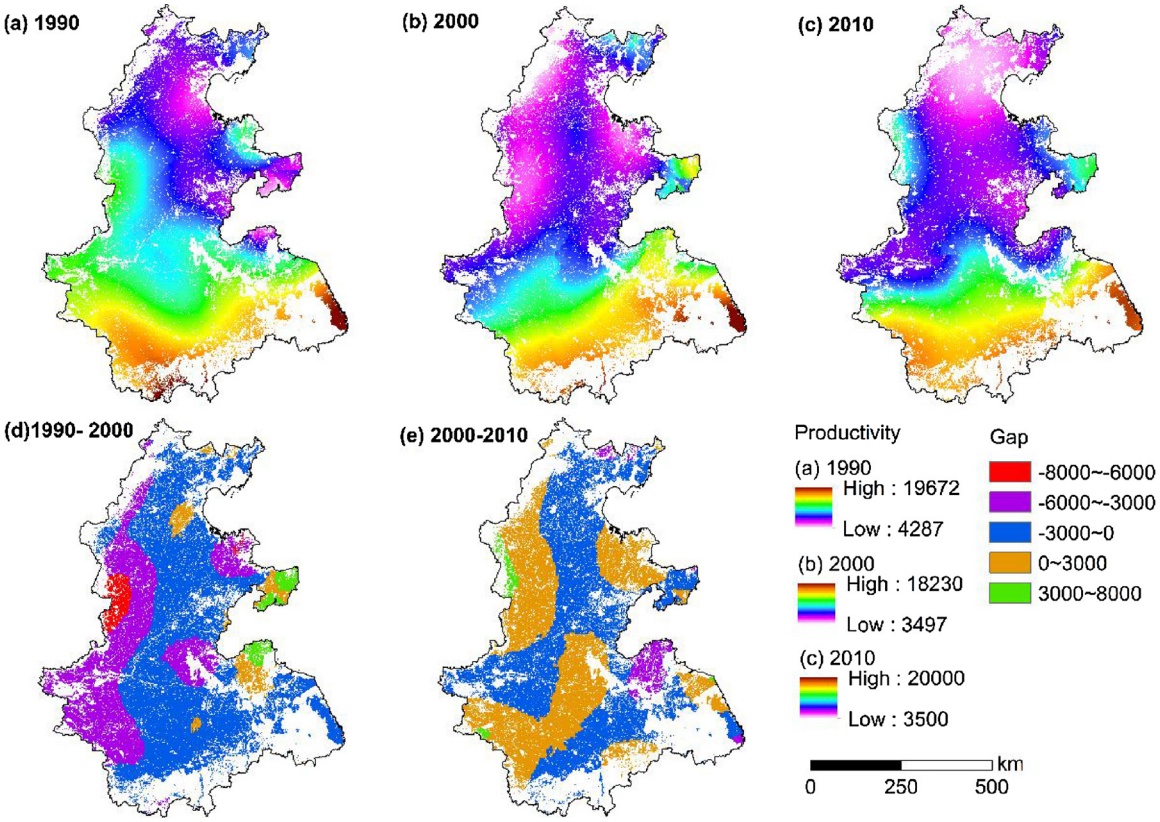

Fig. 3. Spatial distribution of WWCP in the NCP in 1990 (a), 2000 (b), 2010 (c), and spatial distribution of gap of WWCP in the NCP in the period 1990–2000 (d) and 2000–2010 (e). "Gap" is the difference of two periods; for example, "Gap of WWCP in the period 1990-2000" refers to the difference subtracting WWCP in 1990 from WWCP in 2000 on each raster; Gap < 0 denotes a decreasing trend of WWCP that means WWCP in 2000 is lower than WWCP in 1990; Gap > 0 denotes an increasing trend of WWCP that means WWCP in 2000 is higher than WWCP in 1990.

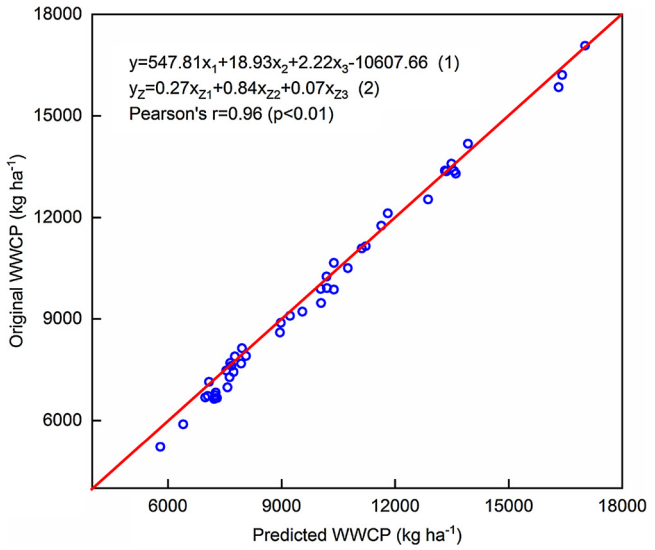

Fig. 4. Comparison of original WWCP and predicted WWCP using station data in 2000s. Eq. (1) is the regression model established from station data in 1980s and1990s, wherey (kg ha^{-1}) stands for WWCP, and x_1 (°C), x_2 (mm), and x_3 (MJ m^{-2}) stand for average temperature, precipitation, and solar radiation during the growing season, respectively. Eq. (2) is the standardized expression of Eq. (1) and the absolute value of its coefficients can reflect the relative importance of the predictor variables in explaining the predictand. The bigger the coefficient, the more important is its effect upon WWCP.

land (18.1% of total area change) with a higher WWCP (over 14,000 kg ha^{-1}) was converted into paddy fields. In this period, the total WWCP from newly-increased dry land could not compensate for the loss from lost dry land, resulting in a 3.96% net reduction of WWCP in the NCP in 2000 compared to 1990. The conversion pattern of dry land, however, was different during the period of 2000–2010. In this period, the reduction in total WWCP from lost dry land was offset by WWCP from newly-increased dry land, which induced a 2.11% net rise in WWCP in the NCP in 2010 compared to 2000. In conclusion, average WWCP values for lost dry land during the two periods were 11,124.03 kg ha^{-1} (1990–2000) and 11,246.87 kg ha^{-1} (2000–2010), both of which were higher than the respective values for newly-increased dry land (10,852.88 kg ha^{-1} in 1990–2000 and 10,507.62 kg ha^{-1} in 2000–2010).

3.4. Comparison of the impact of historic climate variability and land use change on climatic productivity

Fig. 6 presents the average WWCP in the NCP in various periods under the influence of historic variability, land use change, or both. The average WWCP was 9105.83 kg ha^{-1} in reference period (1980s). In both periods of 1990s and 2000s, the isolated effects of historic climate variability or land use change decreased WWCP, but the effects of land use change (within −1%) were smaller than those of historic climate variability (about −3%). Between 1980 and 2010, historic climate variability dominated WWCP changes in the NCP, causing it to decline gradually; this moved from an intensively fluctuating condition in the 1990s to a relatively stable condition in the 2000s, while at the same time land use change strengthened the trend.

Under the combined effect of changes in climate and land use between 1980 and 2010, the WWCP in the NCP also decreased significantly. On average, a −3.36% and −3.72% reduction took place in the 1990s and 2000s, respectively, compared to the reference WWCP. Interactions between climate and land use have always existed. Climate change affects land cover as well as landscapes and thereby alters land use modes; conversely, a change in land use can alter the surface environment and further readjust the water–heat budget, and eventually

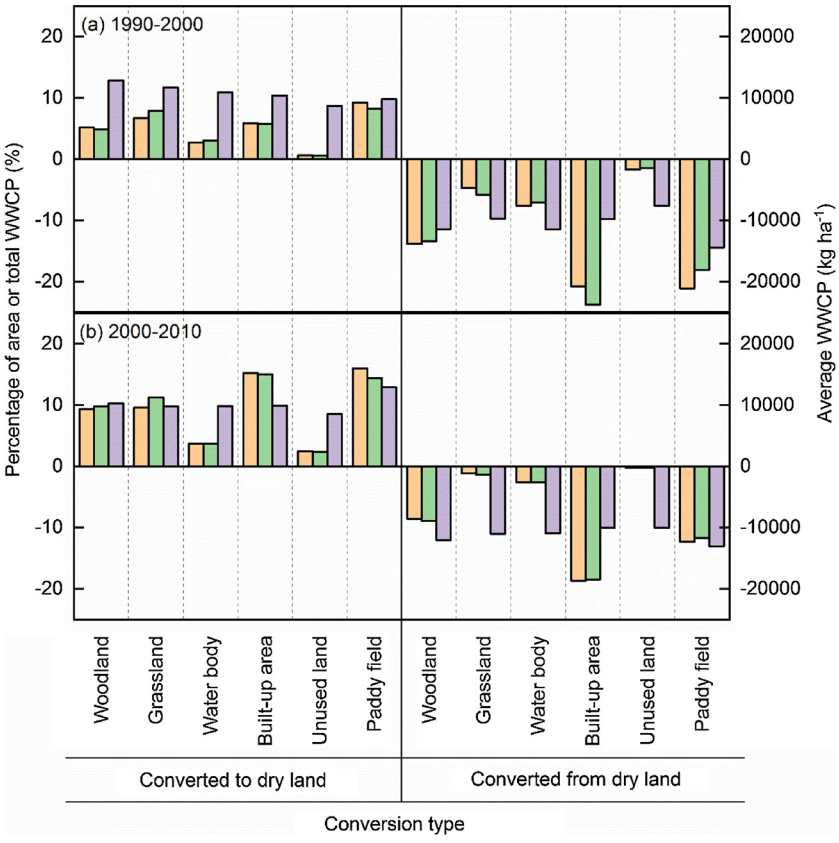

Fig. 5. Percentage of area, percentage of total WWCP and average WWCP of each conversion type in the period of 1990–2000 (a) and 2000–2010 (b).

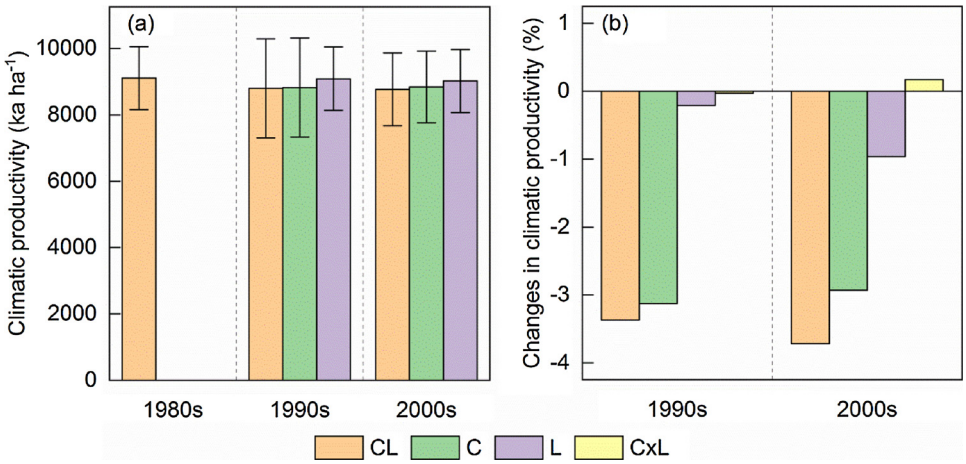

Fig. 6. Climatic productivity of winter wheat under different conditions (a) and its changes induced by different factors (b) in the NCP. The bar indicates the average WWCP and the error bar indicates the standard deviation of WWCP in a certain period. CL: combined effects of changes in climate and land use; C: isolated effects of historic climate variability; L: isolated effects of land use; CxL: effects of interactions between climate and land use.

induce climate change (Butt et al., 2011; Houspanossian et al., 2013; Cho et al., 2014). The interactive effects of historic climate variability and land use change impacted WWCP in different ways in the two periods. These interactive effects caused WWCP to decrease (−0.03%) in the 1990s, but increased WWCP (0.17%) in the 2000s when compared with the reference WWCP. These different impacts are likely due to the different patterns of land use conversion in the two periods as showed in Table 1.

4. Discussion

4.1. Why climatic productivity was more sensitive to precipitation?

The positive relationship between temperatures and WWCP presented in our study contrasts with earlier findings which show that increasing temperatures during the growing season decrease crop yield (You et al., 2009), even after accounting for a reduction in exposure to freezing temperatures during the autumn and winter seasons (Tack et al., 2015). These contrasting findings were possibly due to differences in study regions and scales. Cultivars grown at locations with colder and longer winters have a greater vernalization requirement than those planted where it is warmer in winter (Iwaki et al., 2001). The thermal requirements of wheat for the phenological period from emergence to maturity display a global increasing pattern from north to south (van Bussel et al., 2015). Therefore, although a single positive or negative correlation between climate and crop yield was displayed at a relatively large scale, when this region was separated into several regions at a smaller scale to analyze, relationships between climate and crop yield differed in each region (Chen et al., 2014). For example, Zhang and Huang (2013) discovered that average temperature during the growing season is negatively correlated to wheat yield on a national scale; meanwhile it is positively correlated to wheat yield in mid- and northern China, as well as to maize yield in the eastern part of northeastern China at a county level. Furthermore, the current study also found that precipitation had a much larger influence on WWCP than average temperature during the winter wheat growing season. This discovery is supported by the study of Chen et al. (2013), who note that precipitation was the most essential climatic factor affecting crop yield in the NCP under rain-fed conditions. This could be influenced by crop type, because the sensitivity of different crops to various climatic factors is not the same. Gourdji et al. (2015) reports that beans are particularly sensitive to temperature, whereas maize is more sensitive to water or drought stress, possibly due to its longer growing season. As a corollary of this, it would be reasonable to assume that WWCP was much more sensitive to precipitation than temperature or solar radiation because its growing season is generally longer than that of maize.

4.2. Why land use change reduced climatic productivity?

Our results show that the lost dry land was superior to newly-increased dry land in terms of WWCP during two study periods, which is consistent with results reported in earlier studies. From 1978 to 1998, newly-increased cultivated land was inferior to the lost mature cultivated land in quality because the lost fertilized land in southeastern areas was balanced by newly-increased cultivated land in northwestern areas (Yang and Li, 2000). Due to the discrepancy in quality between the lost and the newly-increased cultivated land from 1986 to 2000, a decline was found in the average potential land productivity of cultivated land in China in 2000 when compared to 1986 (Deng et al., 2006). From 2000 to 2010, urban expansion was the major cause of loss of cultivated land; it accounted for 66.0% of the lost cultivated areas. Over the same period, 76% of newly-increased cultivated land was reclaimed from unused land and grassland. Total grain yield provided by the newly-increased cultivated land could not offset the loss from the lost land, resulting in a net reduction of total yield in China (Liu et al., 2015). In conclusion, the quality as well as productivity of cultivated land has been in continuous decline along with land use change in the past decades. This change is possibly due to the cultivated land conservation policy in China, which did not fully address the protection of land productivity or agriculture production capacity, while emphasizing a guaranteed quantity of land area.

4.3. Policy implications

One key finding in this paper is that changes in the spatial distribution of dry land in the NCP induced a reduction in WWCP, which is likely due to the current cultivated land conservation policy that emphasizes guaranteeing the quantity of land area. Despite the fact that increasing area of dry land provided sufficient wheat yield to compensate the loss resulting from reduction of WWCP in recent years, the approach through expanding the area of cultivated land to maintain grain yield is not a long-term guarantee of food security. The first reason for this is that land is a scarce resource. Competition for various land resources has always existed, because land is needed for food, industrial materials, and for ecological services (Verburg et al., 2013). The second reason is that a large portion of improvement in agricultural production over recent decades has been due to the intensification of agriculture, whereas the contribution from the expansion of cultivated areas has been limited (Rudel et al., 2009; Neumann et al., 2010). The third reason is that the goal of extensive production, achieved by expanding the cultivated area, would incur a high environmental cost and have low economic benefits, and is against the principle of sustainable agricultural development (Tilman et al., 2011). Nowadays, although the real grain yield in much of China has not reached its yield potential

and there remains an abundance of grain growing (Lu and Fan, 2013; Meng et al., 2013), the pressure to improve future grain production is high, because China needs to feed a bigger population in the future. Therefore, the current cultivated land conservation policy should shift from protecting areas of cultivated land to preserving the land productivity or agriculture production capacity.

In addition, results in the current paper show that WWCP was impacted more by historical climatic variability than by land use change in the past few decades in the NCP. Climate change will continuously influence crop production worldwide and the NCP is no exception. Adaptation is inevitable to ensure food security. Before realizing the impacts of climate change on crop production, some autonomous adaptations such as adopting new crop varieties and management options have been proved suitable for achieving high yield under changing climate (Liu et al., 2010; Xiao and Tao, 2014). In addition, it should be noted that responses of crop production to climate change vary across regions (Tao et al., 2013); thus, effective adaptive strategies should be more region-specific (Tao and Zhang, 2010). In particular, a planned adaptation strategy so-called "Double-Delay" technology, which means delayed sowing of wheat crop and delayed harvesting of maize crop (including use of later maturing maize cultivars), has been proved effective for coping with climate change and increasing crop yield in the NCP (Wang et al., 2012). Given that climate change and adaptation is complex, developing strategies for adapting to climate change require innovations in policy and institutions (Zhang et al., 2015). Future agricultural policy should further support studies related to climate-smart agriculture, which have the capacity of providing region-specific adaptive strategies.

Furthermore, the current paper indicates that precipitation is the most critical factor, more so than average temperature and solar radiation, limiting wheat production under rain-fed conditions, which is consistent with earlier studies (Sun et al., 2010; Wang, 2017). This finding emphasizes the critical role of water-saving agriculture for sustainable food production in the study region. The winter wheat/summer maize (WW/SM) rotation system is the main cropping system in the NCP. Given the precipitation pattern in the NCP, irrigation during the summer maize growing season is not necessary (Sun et al., 2011); however, generally 240–400 mm irrigation (4–5 irrigation applications of 60–80 mm each) during the winter wheat growing season is required for achieving high yield (Sun et al., 2010). In this region, groundwater is the main source for irrigation. The high demand for agriculture irrigation (especially winter wheat irrigation) is considered the major reason for groundwater overexploitation, which causes a rapid decline in groundwater table (Yang et al., 2006; Qiu, 2010). As a result of this situation, water-saving agriculture has obtained wide attention from both scholars and policymakers.

Related studies show that applying irrigation at the critical stage can effectively increase water use efficiency. However, even the minimum irrigation will cause a decline in groundwater table (Sun et al., 2015). Although zero irrigation in rain-fed agriculture will not lead to a decline in the groundwater table (van Oort et al., 2016), yield gap under this condition is rather large (Sun et al., 2015). A possible solution to balance water consumption and grain yield may be to reduce winter wheat acreage or shift the current WW/SM cropping system to more water-saving ones. A recently published paper proves that cropping system optimization can effectively mitigate groundwater decline and maintain grain production. The preferred alternative system is the three harvests in two years system (1st year: WW/SM; 2nd year: early maize) (Luo et al., 2018). As a consequence, the government emphasized limiting high water consumption crops in the NCP and moderately reducing winter wheat acreage in the groundwater overdraft region in the Central Document No.1 released in 2016. In 2017, this document emphasized again that the large-scale implementation of agricultural water-saving projects is a strong push for guaranteeing water and food security. The core of water-saving agriculture is to improve water (both precipitation and irrigation) use efficiency or productivity without impairing grain production and economic return. Therefore, future agriculture policy should further emphasize balancing crop production and groundwater use for improving sustainability.

5. Conclusion

The current study estimated winter wheat climatic productivity (WWCP) in the North China Plain (NCP) from 1980 to 2010 and also qualified and separated the impacts of historic climate variability and land use change on WWCP. Results indicate an obvious interannual fluctuation of WWCP, as well as a spatial distribution pattern: The WWCP in the southern part of the NCP was higher than in the northern part. The three climatic factors (average temperature, precipitation, and solar radiation) were positively correlated with WWCP, but precipitation was the most important. In addition, during each of the periods 1990–2000 and 2000–2010, average WWCP in newly-increased dry land was lower than that in lost dry land, which indicated that land use change would reduce WWCP, and was therefore deleterious to winter wheat production. To some extent, this also indicated that the quality of dry land was damaged to some extent during land conversion. Both historic climate variability and land use change decreased WWCP, but the effects of land use change were smaller than those of historic climate variability. During the study period, the declining trend in WWCP was dominated by historic climate variability, with land use change exacerbating this trend. Based on these results, some useful implications of agriculture and land policy have been generated: (1) Future cultivated land conservation policy should focus on protecting land productivity or agriculture production capacity. (2) Future agriculture policy should further support studies related to climate-smart agriculture for coping with climate change. (3) Future agriculture policy needs to further emphasize balancing crop production and groundwater use for improving sustainability.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.landusepol.2018.04.018.

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